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Estimation of anti-fouling paint thickness and its use in extending the lifetime of a ship's underwater hull coating system

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ESTIMATION OF ANTI-FOULING PAINT THICKNESS AND ITS USE IN EXTENDING THE LIFETIME OF A SHIP'S UNDERWATER HULL COATING SYSTEM

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ABSTRACT

The underwater hull paint system on an aircraft carrier is comprised of anti-corrosive (AC) and anti-fouling (AF) paint. The AF paint is designed to continuously ablate during the ship's operational cycle, releasing toxins that inhibit marine growth on the hull's surface. In 1997, Whitaker, Wimmer, and Bohlander performed a least squares regression to develop a model that predicts the total coating system wear using dry film thickness (DFT) measurements taken in drydock. The model is derived without use of data taken by remotely operated vehicles (ROV), which measure paint thickness underwater with the potential for variations due to paint swell. An analysis of data taken by ROV is performed here with an attempt made to modify the existing model to include its use. Also, the model has no mechanism to account for the application of additional layers of AF paint at an interim drydock, making it unreasonable to use the model to predict the distribution of paint thickness following two operational cycles with an interim painting. To allow for this prediction, an estimate for the mean thickness of one coat of AF paint is determined. Using this determined estimate and the mean of the predicted distribution for the interim drydock, a simple method is derived for estimating the mean thickness of a hull's total coating system following two operational cycles. This method provides enough information to facilitate deciding in advance how many coats of AF paint to apply at that interim drydock to ensure hull integrity is maintained until the second drydocking evolution.

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LIST OF ABBREVIATIONS

AC	Anti-corrosive
AF	Anti-fouling
NSWCCD	Naval Surface Warfare Center, Carderock Division
PERA(CV)	Planning and Engineering for Repairs and Alteration command for U.S. Navy aircraft carriers
COMNAVAIRLANT	Commander Naval Air Forces, U.S. Pacific Fleet
COMNAVAIRPAC	Commander Naval Air Forces, U.S. Atlantic Fleet
ROV	Remotely Operated Vehicle
DFT	Dry film thickness
NSTM	Naval Ships' Technical Manual
SHOMACS	Ship's Hull Operational Wear Model for Ablative Coating Systems

EXECUTIVE SUMMARY

The Navy currently spends about $80 million annually on ship hull preservation, with the process of repainting one ship contributing approximately $3 million to that total. It is investigating ways to extend the lifetime of the underwater hull coating systems of its ships in an attempt to reduce drydock costs. One means of extension is to "reuse" existing coating systems by adding coats of paint at an interim drydock, hence reducing the number of complete removals and repaintings needed.

The underwater hull paint system on a ship is comprised of two types of paint: anti-corrosive (AC) and anti-fouling (AF). Newly painted ships in operation today have systems that consist of 2-3 layers of AC paint followed by 3-4 layers of AF paint. The AF paint is designed to continuously wear away (or ablate) during the ship's operational cycle, releasing toxins that inhibit marine growth on the hull's surface. The lifetime of a hull paint system, defined as the time until the hull must be "blasted clean" and repainted, can be determined by how much AF paint remains from the initial drydock to a follow-on drydock.

The Navy's current guidance on painting, maintaining, and evaluating hull paint systems is the Naval Ships' Technical Manual (NSTM). Chapter 631 provides guidance on the evaluation of a hull paint system. Whitaker, Wimmer and Bohlander (1997) show that this instruction is based on faulty assumptions. They perform a least squares regression to develop a model that better estimates total coating system wear using dry film thickness measurements taken in drydock. This model is derived without use of data taken by remotely operated vehicles (ROV), which measure paint thickness underwater with the potential for variations due to paint swell.

Using data collected from the fleet's aircraft carriers, an analysis is performed of data taken by ROV with an attempt made to modify the existing model to include its use. Further analysis is performed which provides a means for determining how many coats of AF paint need to be added to an existing hull coating system at the end of the interim drydock in order to ensure that the hull is protected for an additional operational cycle. An estimate for the mean thickness of one coat of AF paint is determined in order to allow for this prediction. Using this determined estimate and the mean of the predicted distribution for the interim drydock, a simple method is derived for estimating the mean thickness of a hull's total coating system following two operational cycles. This method provides enough information to facilitate deciding in advance how many coats of AF paint to apply at that interim drydock to meet the goal.

The enhancement of past research with the method derived in this analysis will result in a more quantitatively-based estimation of a ship's hull paint thickness. Having the benefit of this knowledge, planners can omit the costly occurrence of unnecessary paint system removals by effectively scheduling future hull maintenance procedures to include the less expensive alternative of AF paint addition. This entire analysis was done only using aircraft carriers, but the information gained should serve as a conservative estimate for all types of ships in the fleet, as aircraft carriers typically have more intense operational schedules than other surface ships.

I. INTRODUCTION

The process of planning an overhaul for a ship is a multi-faceted evolution. When a ship is commissioned or released at the completion of a shipyard evolution, Commander Naval Air Force, U.S. Atlantic Fleet (COMNAVAIRLANT) and Commander Naval Air Force, U.S. Pacific Fleet (COMNAVAIRPAC), along with shipyard supervisors and maintenance planners, collaborate to schedule its next overhaul. This determination is made based mainly on the technical requirements of the ship, with financial and political issues also being considered. Technical requirements include evaluation of the wear of systems aboard the ship, such as valve systems, paint systems, propellers and rudders, and internal components. The additional requirement of the life of the power plant must also be considered if the vessel is nuclear powered. Financial and political considerations include budget constraints, the ship's remaining life in the fleet, which facility will be performing the repairs, and the extent of the repairs needed.

The Navy currently spends about $80 million annually on the hull preservation of its ships. The process of repainting one ship contributes approximately $3 million to that total [Ref. 20]. It is investigating ways to extend the lifetime of the underwater hull coating systems of its ships in an attempt to reduce drydock costs. One means of extension is to "reuse" existing coating systems by adding coats of paint at an interim drydock, hence reducing the number of complete removals and repaintings needed.

The underwater hull paint system on a ship is comprised of two types of paint: anti-corrosive (AC) and anti-fouling (AF). Newly painted ships in operation today have systems that consist of 2-3 layers of AC paint followed by 3-4 layers of AF paint. The AF paint is designed to continuously wear away (or ablate) during the ship's operational cycle, releasing toxins that inhibit marine growth on the hull's surface. The lifetime of a hull paint system, defined here as the time until the hull must be "blasted clean" and repainted, can be determined by how much AF paint remains from the initial drydock to a follow-on drydock.

Using data collected from the fleet's aircraft carriers, this analysis aims to provide a means for determining how many coats of AF paint need to be added to an existing hull coating system at the end of the interim drydock in order to ensure that the hull is protected for an additional operational cycle.

A. BACKGROUND

Shipyard guidelines for estimating the repair costs for ship's hull paint system are set forth in the Standard Items 009-31 directive [Ref 9]. In the past, this directive utilized the worst-case scenario that the hull would need to be blasted clean and repainted. For planning purposes, this approach proves to be costly, resulting in salvageable paint systems being completely removed. The Naval Surface Warfare Center, Carderock Division (NSWCCD) has been tasked by the Planning and Engineering for Repairs and Alteration command for U.S. Navy aircraft carriers (PERA(CV)) to provide technical support to COMNAVAIRLANT and COMNAVAIRPAC in the areas of paints, coatings, corrosion control and composites on aircraft carriers in an attempt to provide a quantitative means to more efficiently determine hull paint system maintenance cycles [Ref. 1]. This tasking involves monitoring and documenting paint application in drydock and performing and documenting periodic underwater hull inspections with divers or remotely operated vehicles (ROV). The purpose of the tasking is to analyze the wear and maintenance of the AF paint layer and then use this analysis as an aid to facilitate extending the lifetime of a ship's underwater hull paint system.

One method used to document the final paint film thickness for preservation purposes involves taking dry film thickness (DFT) measurements. DFT gauges, varying in size from hand-held portables to rugged shore-power-supplied units, measure the variation in magnetic force between a metal surface and their self-contained permanent magnets. Instruments are available for use in drydock settings as well as underwater while the hull is submerged. When the probe of the gauge is placed perpendicular to the surface of the ship, the gauge returns a measurement that represents the distance from the probe to the metal surface beneath in units of mils, with one mil equal to 1/1000 of an inch.

The Navy's current guidance on painting, maintaining, and evaluating hull paint systems is the Naval Ships' Technical Manual (NSTM). Chapter 631 provides guidance on the evaluation of a hull paint system [Ref. 14]. Whitaker, Wimmer and Bohlander (1997), henceforth referred to as WWB(1997), show that this instruction is based on the inaccurate assumptions that paint application is uniform and that total paint thickness reflects the thickness of the AF layer. They also show that the instruction doesn't take into account uneven wear as a function of ship's operational cycle and number of hull maintenance procedures performed. As a result, the "one size fits all" paint system evaluation that requires an average total coating thickness of 24-25 mils is inadequate in ensuring the hull will be protected over lengthy periods of time.

WWB(1997) presents a more accurate means to determine survivability of a ship's hull paint system by using the distribution of the paint thickness and how it changes with wear due to time at sea, number of hull cleanings and number of hydro-washes. Using data collected from aircraft carriers in drydock from 1985-1997, it describes a least squares regression that develops a wear model that predicts total coating system wear. The model is then tested on thickness measurements taken from the CV 59, a validation data set separate from the development data. The model tests well, predicting a distribution of paint thickness that was remarkably close to the hull's actual distribution of paint thickness. WWB(1997) also contains the Ships Hull Operational Wear Model for Ablative Coating Systems (SHOMACS) program, an Excel '97 spreadsheet created to implement the wear model.

B. SUMMARY OF DATA

Appendix A contains a table listing of all data sets that were available prior to the analysis performed in this paper. However, two sets of data from CVN 74 contain peculiarities that are worth noting. The data set taken in 1993 contains a sorted version of the raw data that lacks credibility because it does not match the raw version. The raw data is used in this analysis. Another data set taken in 1996 contains measurements which suggest that, despite almost three years of operation at sea and a hydro-wash prior to indock measurements, the paint system thickened dramatically. Approximate actual increases in paint thickness of 3.5 and 13.3 mils are noted at the median and ninetieth percentiles respectively. This data set is excluded from any analysis.

C. METHODOLOGY

The predicted distribution of the total coating system provides a wealth of information about what to expect in one operational cycle. However, the model does have limitations. First, the longest operational cycle available for use in the derivation of the model is eight years. Second, it is based on the small sample of six data sets. Third, it has no mechanism to account for the application of additional layers of AF paint at an interim drydock. Fourth, the model is derived without the use of data taken by ROV, which occurs underwater and may have an effect on the paint system due to a phenomenon called swell. Finally, the distribution of a single layer of AF paint, which is required to estimate the effects of its application on the paint system, is unknown and difficult to estimate [Ref. 20]. With these unknowns, it is not reasonable to use the wear model directly to predict the distribution of paint thickness for the Navy's goal lifetimes of 12 years or more with paint added at an interim drydock. However, using the estimated mean of the predicted distribution for the interim drydock provided by SHOMACS and the estimated mean thickness of one coat of AF paint, enough information may be provided to make a decision about how many coats of AF paint to apply at that interim drydock.

In Chapter II, the WWB(1997) wear model is tested with newly collected data for validation or, if necessary, modification. In Chapter III, an evaluation of prediction models using data collected with the ROV is performed. In Chapter IV, an estimate for the mean thickness of a single layer of AF paint from actual data is derived. A mathematical model to predict the mean thickness of the distribution following two operational cycles using the WWB(1997) wear model and the mean AF thickness estimate is developed in Chapter V. An illustration of the use of this model is also included in this chapter. Chapter VI concludes the analysis with recommendations and discussion.

II. VALIDATION OF THE WWB (1997) WEAR MODEL

In deriving the model for the wear of a ship's hull paint system, WWB(1997) sought to answer the question, "Does this coating system possess sufficient AF paint to adequately endure the ship's projected operational and maintenance cycle?" Exploratory analysis revealed that changes in a ship's coating system thickness distribution depended on the length of the operational cycle, the number of underwater hull scrubbings, called hull cleanings, performed during that operational cycle and the number of high pressure water washes, called hydro-washes, performed during that operational cycle. Analysis also revealed that changes in the quantiles of a coating system's thickness before and after hull maintenance procedures and operational cycles were roughly linear, thus allowing WWB(1997) to further develop a quantitative model that predicts coating system wear.

A. THE WWB(1997) WEAR MODEL

Using five sets of data from CV59, CVN 68, CVN 69 and CVN 72, the WWB(1997) model gives the following least squares approximation for y_p, the difference in the p^{th} quantile before and after an operational cycle, for p = 10,11,. . . 90,

$$y_p = -1.8175 + .0465p + .4616D + 5.3411C + 4.640W + .0021pD - .042pC - .0527pW,$$

where p, D, C and W represent percentile, duration of operational cycle, number of hull cleanings and number of hydro-washes respectively. The assumptions needed for inference based on Normal linear model theory, specifically independence, were not met by the data, so standard errors were not computed for this model. However, the model gave a squared multiple correlation coefficient of 0.983, indicating a good fit [Ref. 20].

B. VALIDATION

Since the development of the quantitative wear model, new data has been collected from additional aircraft carriers [Ref. 1,5-7,13,17]. Information recorded for each ship includes the number of hull cleaning and hydro-wash procedures performed during the operational cycle and the length of the operational cycle, computed as the actual elapsed time between the dates of the initial and final sets of measurements. Table 1 summarizes the data to be used in the validation process.

Hull Number	Operational Cycle Length (years)	No. Hull Cleanings	No. Hydro-washes	Measurement Type: Before-After
CV 67	2.417	0	0	Drydock-ROV
CVN 68	4.250	0	0	Drydock-Drydock
CVN 71	5.417	0	1	Drydock-Drydock
CVN 73(a)	4.500	0	0	Drydock-ROV
CVN 73(b)	5.417	0	0	Drydock-Drydock
CVN 74	2.917	0	1	Drydock-ROV

Table 1. Summary Data Used in the Validation Process.

For the purpose of predicting how the paint wears, Figure 1 compares the differences between the actual and predicted total thickness measurements for percentiles 10 through 90 following the above listed operational cycles. Initial inspection of this figure indicates that the WWB(1997) wear model is providing a good approximation of the empirical cumulative distribution functions (cdf's) of the coating systems for the data sets. Note from Figure 1 that, in all cases, the difference between the predicted and actual median thickness values remains within an absolute measurement of 2.5 mils, slightly more than half the four mil thickness of a single coat of AF paint by NSTM standards. Also note that the largest differences occur at the extreme percentiles, 10 and 90, with the largest difference occurring at the ninetieth percentile for CVN 73(a) with a magnitude value of 5.57 mils, slightly over a single coat of AF paint by NSTM standards.

Thus, for practical purposes, this accuracy should suffice for making a decision about how many coats of paint to add.

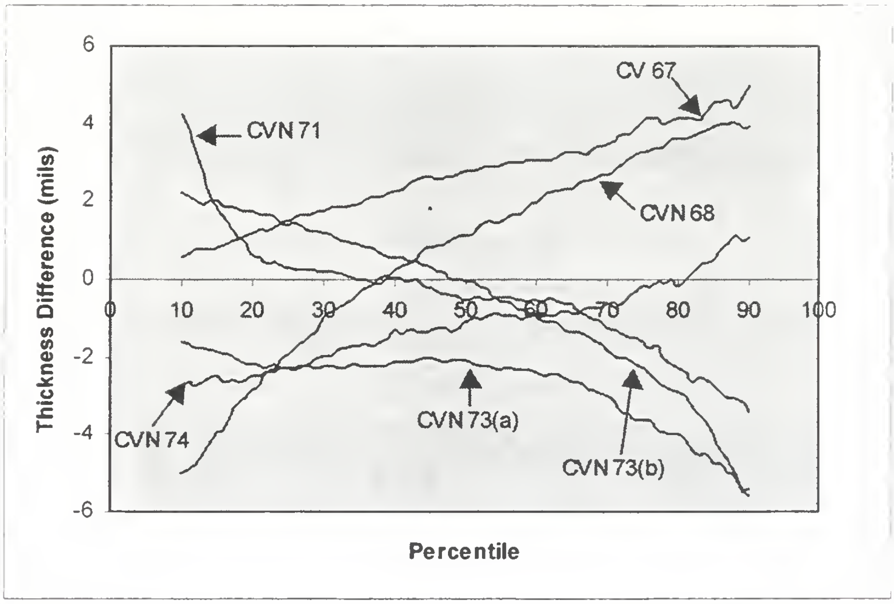

Figure 1.Difference between actual and predicted percentiles of the total thickness after an operational cycle.

Taking a closer look at the cdf's for each ship individually, Figures 2 through 7 compare the actual and predicted empirical cdf's for the ships following the noted operational cycles, hull cleanings and hydro-washes as computed using the wear model. Notice that, with the exception of the data set from CV 67 depicted in Figure 5, these individual cdf's also indicate good approximations by the WWB(1997) wear model. The Navy is concerned with excessive hull surface fouling, which can reduce a ship's performance, and hull surface corrosion, which can result in hull watertight integrity breaches [Ref. 20]. Both situations result in long, costly repairs during drydocking evolutions. For this reason, the area of concern in Figures 2 through 7 is the area defined by the thinnest paint thickness values.

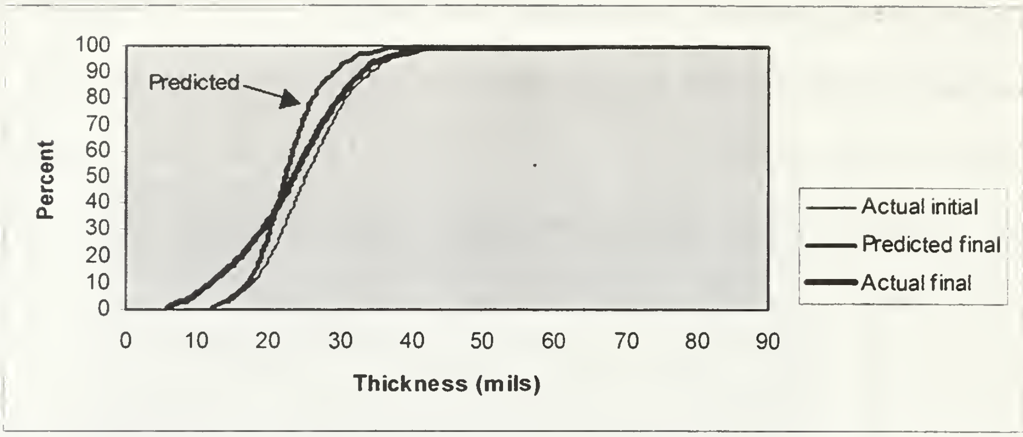

Figure 2. Model Validation—Predicting the coating system distribution of CVN 68.

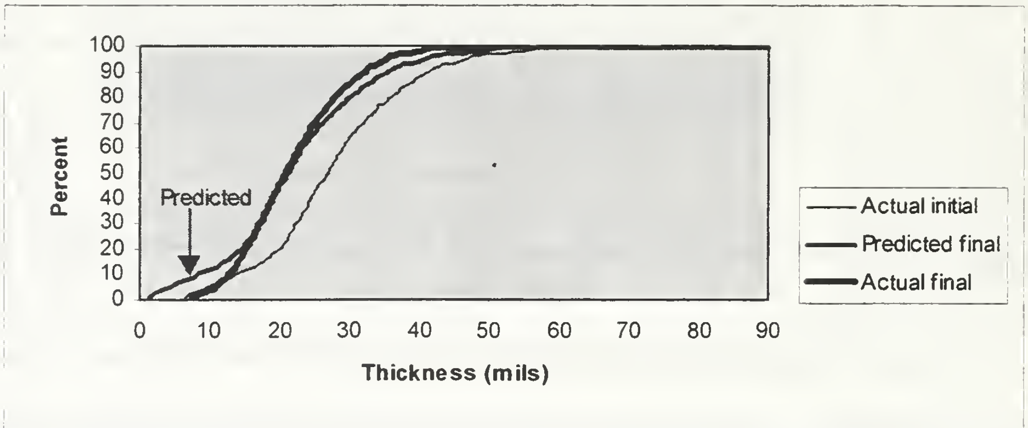

Figure 3. Model Validation—Predicting the coating system distribution of CVN 71.

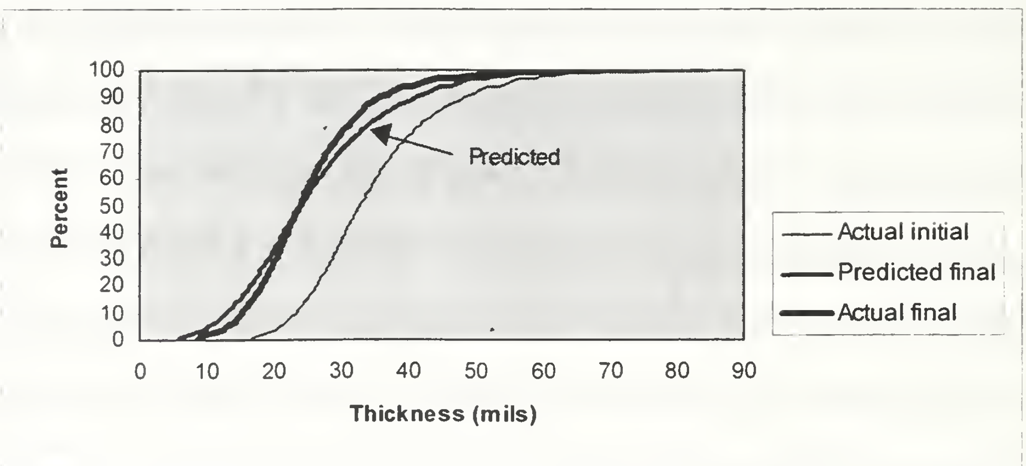

Figure 4. Model Validation—Predicting the coating system distribution of CVN 73(b).

For CVN 68, depicted in Figure 2, the hull is estimated to have no less than 12 mils of total paint remaining after 4.25 years of operation with no hull maintenance procedures performed. Since current guidelines set forth by the NSTM estimate that the AC layers of paint contribute approximately 12 mils to the total paint thickness, use of the model indicates that the hull is in no danger of severe fouling or corrosion failure [Ref. 14]. Actual measurements show that ten percent of the hull coating system is below 12 mils in thickness.

The model produces a more conservative prediction for CVN 71, depicted in Figure 3, estimating that approximately 20 percent of the hull coating system would have a total thickness of 12 mils or less following five or more years of operation and one hydro-wash procedure. No AF paint would exist on a significant portion of the hull. From this, it is anticipated that serious fouling will occur. It can be then determined that either the length of the operational cycle needs to be reduced or additional coats of AF paint need to be added before the ship leaves the drydock. Final measurements show that, in actuality, eight percent of the hull has less than 12 mils of paint in the follow-on drydocking with no additional paint added.

Estimates for CVN 73(a), CVN 73(b) and CVN 74, depicted in Figures 4.6, and 7, are very close to actual measurements. All three indicate no potential for severe fouling or corrosion failure.

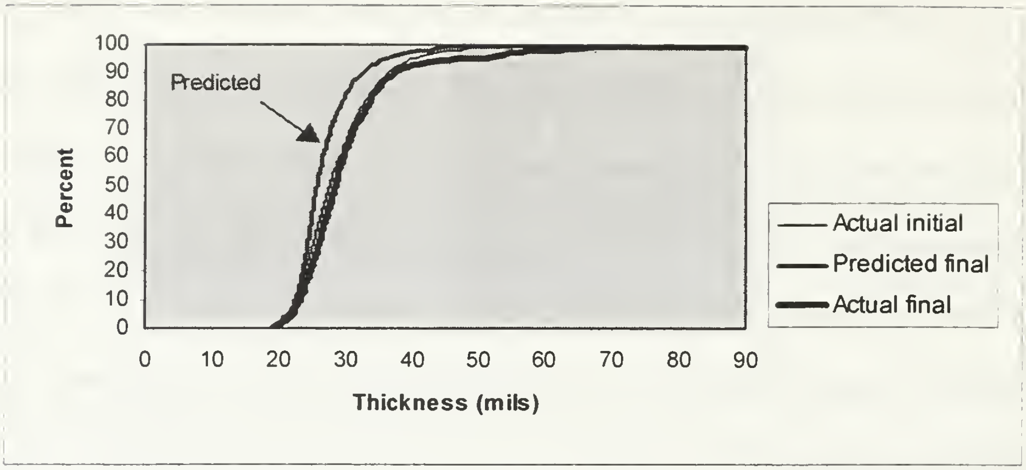

Figure 5. Model Validation—Predicting the coating system distribution of CVN 67.

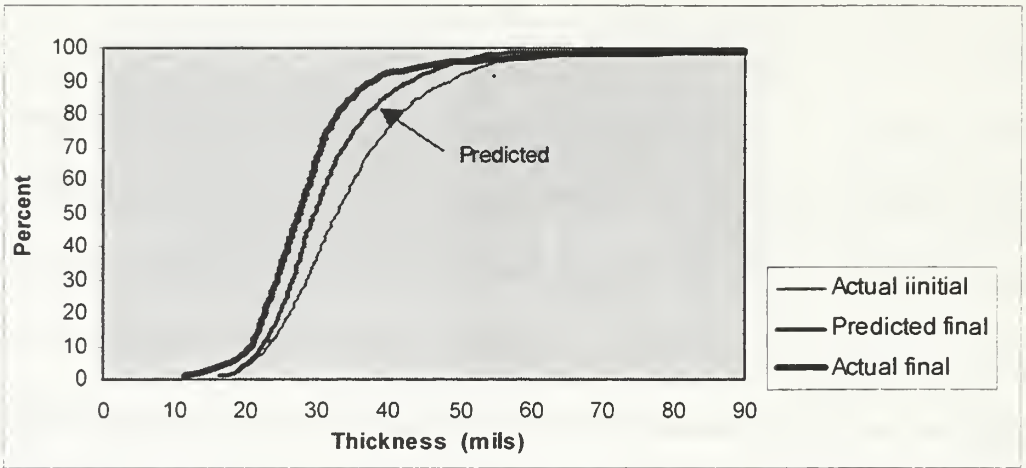

Figure 6. Model Validation—Predicting the coating system distribution of CVN 73(a).

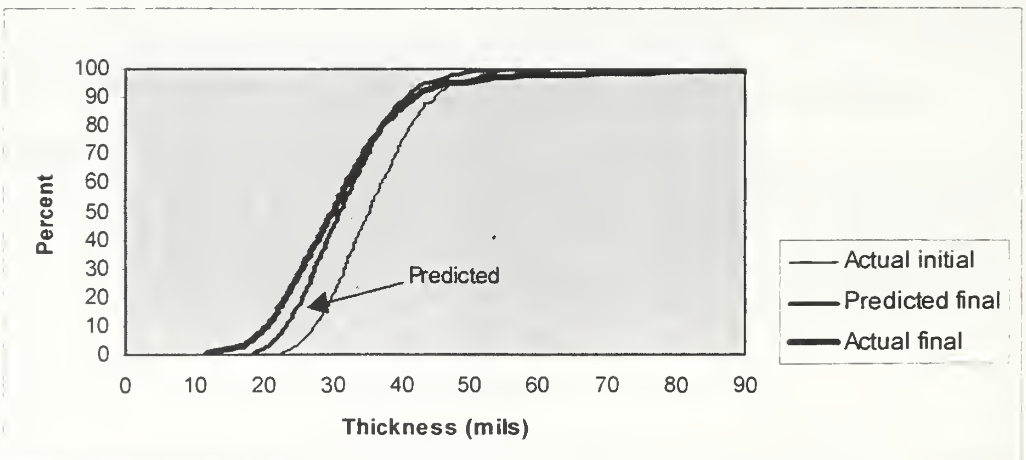

Figure 7. Model Validation—Predicting the coating system distribution of CVN 74.

Notice that Figures 5, 6 and 7 contain final sets of data that were taken with the ROV which, as stated earlier, was not used in the creation of the wear model. Although Figures 6 and 7 indicate that this different type of data did not affect the prediction of wear, the effects of the phenomenon called swell could serve as the explanation for the variation in Figure 5. This issue is addressed in the next chapter.

III. ANALYSIS OF MEASUREMENTS TAKEN BY REMOTELY OPERATED VEHICLES

There are currently two models of remotely operated vehicles (ROV), S2 and HVS4, available from Deep Ocean Engineering. Each ROV is equipped with a paint thickness measuring probe, a silver/silver chloride reference cell for impressed current cathodic protection potential data and a color video camera for recording video and still photography. It has a 500-foot umbilical connected to a control console in a support van on the pier. The ROV is directed manually around the hull. The paint thickness probe is deployed to collect data at various locations distributed over the hull below the water line. The data is transmitted topside, where it is stored in a data acquisition program on a laptop computer [Ref. 5, 6]. In Chapter II, Figure 5 indicates that the WWB(1997) wear model is not always producing consistent results when data taken from an ROV is used. Possible explanations for this variation include the actual taking of the measurements and swell.

It has already been stated that the probe of the gauge must be perpendicular to the surface of the ship in order to get an accurate measurement of the paint thickness. However, the gauge will record a reading even if the probe is not perpendicular to the surface. Since the ROV is submerged and maneuvered remotely from a pier, it is very difficult to determine if the probe is perpendicular to the surface of the ship, especially when maneuvering around the curves of the hull. Thus, some of the readings retrieved are not accurate representations of hull paint thickness.

When an object is submerged in water for an extended period of time, the water can permeate the fibers of the object, causing the surface of the object to become bloated. This bloating of the object is called swell. If measurements of any type are taken of the object while underwater, it is expected that the measurements would be inflated in comparison with the same measurements taken on the object once dry. This very phenomenon, if occurring on the hull of the ship while it is submerged, could cause those measurements taken with the ROV to indicate thicker paint than is actually on the hull.

Both of the variations in measurements listed above are not currently accounted for in the WWB(1997) wear model. The data must be reassembled as a first step in modifying the original model,. In search of the original data, the set for CV 59, which was data taken over a hull cleaning, could not be located. Since the data for CVN 69(b) contained 2 hull cleanings, the assumption that the effects of a hull cleaning were accounted for is made, and the linear regression is performed without the CV 59 data set. The following model results,

$$y_p = -6.9470 + .1334p + 1.4665D + 3.3205C + 9.8125W - .0150pD - .0168pC - .1403pW.$$

As in the WWB(1997) model, this model has a large squared multiple correlation coefficient, 0.991. To see how close this is to the original model, this model's prediction is compared to the original prediction for CVN 73(a). Figure 8 shows the results of the comparison. Notice that the two predicted distributions are virtually superimposed, appearing as a single curve. Thus, the assumption that the hull cleaning information is accounted for in the other data sets used to create the original model is verified.

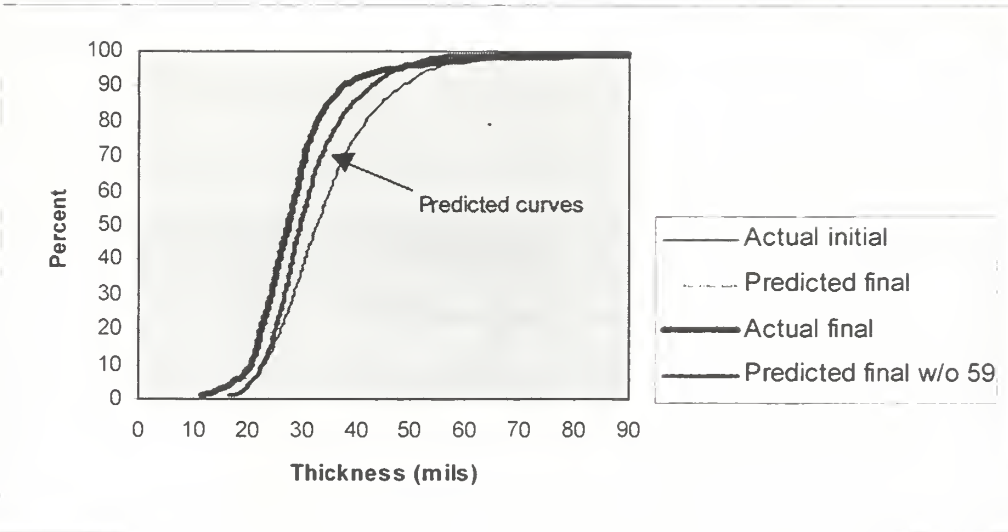

Figure 8. Model Comparison—Predictions for CVN 73(a) with and without data from CV 59.

Next, a new random variable R is created; specifically, R = 1 if the final set of measurements used in the prediction is taken with an ROV, and R = 0 if not. ROV data sets from CVN 67 and CVN 74 are then added to this modified data set, and a linear regression is performed. The following least squares approximation for y_p results from that regression. It produces a squared multiple correlation coefficient of 0.994.

$$y_p = -6.9470 + .133p + 1.4665D + 3.3549R + 3.3205C + 9.8125W - .0150pD$$
$$+ .0417pR - .3720DR - .0168pC - .1403pW - .0563pDR.$$

When the variable R = 0, this model reverts back to the wear model derived without the use of the ROV term. Thus, it is only necessary to check its validity for the data sets that contain ROV measurements. The remaining ROV data set, CVN 73(a), is checked. Figure 9 shows the output from the model. This model is not accurately predicting the wear of paint for this ship, overestimating the total thickness of the system with an error of 2.54 mils at the tenth percentile and 22.65 mils at the ninetieth percentile. Having only three sets of ROV at the present, there is not enough data to do a more in-depth evaluation of what happens with the addition of measurements from ROV's to the model. Since the original WWB(1997) model did give more accurate predictions for the majority of the data sets currently available, both drydock and ROV, this model will be used for the remainder of this analysis. The topic of the effects of swell on prediction is left as a topic for future research when more data is available.

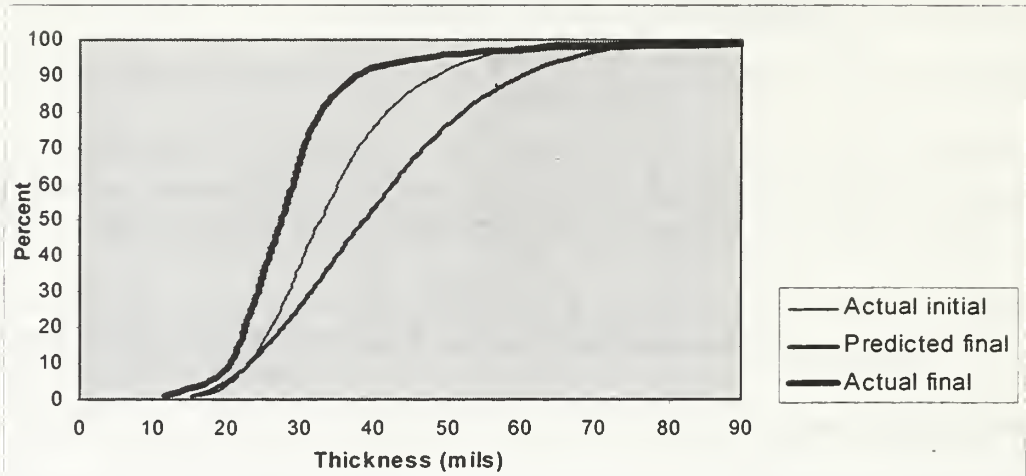

Figure 9. Model Validation—Predicting the coating system distribution of CVN 73(a).

IV. DETERMINING THE MEAN THICKNESS OF A COAT OF ANTI-FOULING PAINT

Knowledge of the distribution of the thickness of one coat of AF paint is necessary in order to get a precise estimate of how much paint to add at an interim drydock. With the estimation of the distribution of a single coat of AF paint being difficult to acquire, another approach that can be used to determine how much paint to add at the interim drydock involves estimating the mean of a single coat of AF paint and using this mean to get an estimate of the mean thickness of a paint system at some point in the future. In this chapter, an attempt is made to derive an estimate for the mean thickness of a single coat of AF paint using total paint thickness measurements.

Four sets of data are currently available for use in determining the distribution of a single coat of paint.

- 1985: an indock set of measurements after the application of two AC coats of paint and a final set of measurements after the application of four coats of AF paint for CVN 69.
- 1995: an indock set of measurements following ship drydocking and a hydro-wash and a final set of measurements following the application of two coats of AF paint for CVN 69.
- 1998: an indock set of measurements upon ship drydocking and a final set of measurements following a hydro-wash and the application of two coats of AF paint for CV 63.
- 1998: an indock set of measurements following ship drydocking and a hydro-wash and a final set of measurements following the application of one coat of AF paint for CV 64.

In an exploratory look at the data sets listed above, Figures 10 through 13 show the frequency histograms for the total coating system thickness for CV 63, CV 64 and CVN 69. It is obvious from the figures that the distribution of total paint thickness is very variable from one hull painting to the next.

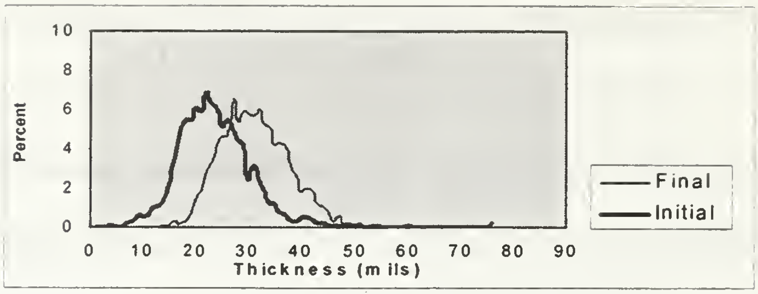

Figure 10. CV 63 hull coating system thickness before and after two AF paint coats.

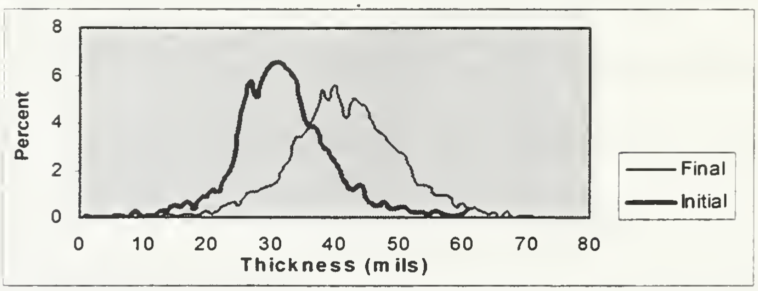

Figure 11. CV 64 hull coating system thickness before and after one AF paint coat.

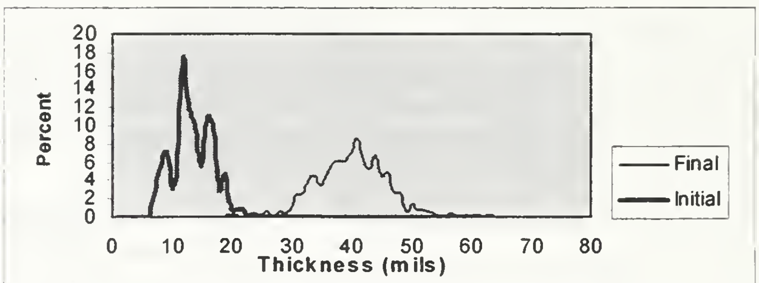

Figure 12. CVN 69 hull coating system thickness before and after four AF paint coats.

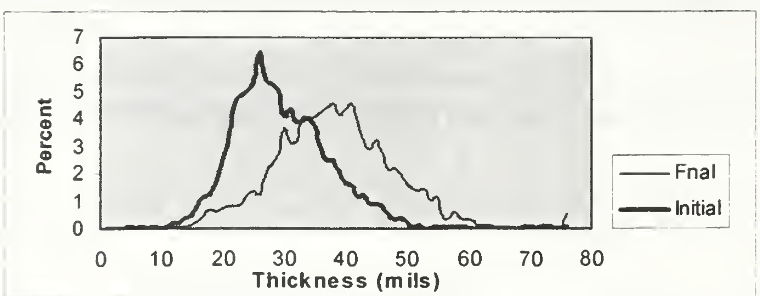

Figure 13. CVN 69 hull coating system thickness before and after two AF paint coats.

To estimate the mean of a single coat of AF paint, it is necessary to assume that its value remains constant from application to application. This assumption does not immediately seem reasonable, but with the sparse amount of data currently available for analysis of the mean thickness of a coat of AF paint from application to application, it is a logical baseline assumption. As more information is known specifically pertaining to AF paint application, this assumption may require modification.

An estimate of the mean single coat thickness for each data set listed above is computed by calculating a mean paint thickness value of the initial and final data, taking the difference between the two values and dividing that difference by the number of coats of paint added. Since CV 63 was hydro-washed prior to the additional paint being added. the paint taken off by the hydro-wash needs to be subtracted. Thus, the initial mean value used for this set of data is modified by subtracting the coefficient for hydro-washes found in the WWB(1997) model (4.6404 mils) from the mean value calculated from the initial data. Table 2 summarizes the estimated mean values. As anticipated, notice the variation in the estimated mean thickness of one coat of paint.

Hull Number	**Est. Single Coat Mean Thickness (mils)**
CV 63	5.910
CV 64	9.551
CVN 69-85	6.670
CVN 69-95	4.384

Table 2. Computed mean AF thickness values.

If the thickness of a coat of AF paint at a specific location is independent of the paint added prior to its application, it is reasonable to conclude that an estimate of mean thickness derived from the application of four coats of paint will have greater variability than one derived from the application of one coat of paint. Thus, under this additional assumption of independence in coating thickness between applications, a reasonable approach to combining the estimates of Table 2 into a single estimate of mean thickness for a layer of AF paint would weigh the individual averages based on the number of layers of paint from which they were derived, giving those derived from fewer coats of paint more weight.

Under this new assumption of independence, we expect the variability of total thickness to increase with number of coats. However, notice in Table 3 that the variability of paint thickness is not always increasing with the addition of paint. CV 63, which had two coats of AF paint added to its hull, underwent a marked decrease in total paint thickness variability. Random error in the estimates of the variances is not a likely explanation for any changes in variability for these data sets because over 2,500 data points are used in the estimation process. Thus, there is an indication that something else may be having an affect on the paint.

Hull Number	**Initial Variance (mils^2)**	**Final Variance (mils^2)**
CV 63	59.035	41.779
CV 64	57.026	72.905
CVN 69-85	10.735	39.797
CVN 69-95	65.711	100.801

Table 3. Computed total paint thickness variance values.

The description of the painting evolution for CV 63 reveals that its hull was painted in the month of March. Descriptions of the painting evolutions for CV 64, CVN 69-85 and CVN 69-95 reveal that all three hulls were painted in the months of June and July. One possible explanation for variability, involving temperature, is as follows. When the hull is painted in warmer months, the surrounding heat aids in drying the paint on the surface fairly quickly. Thus, the paint has less opportunity to shift, and the assumption of specific-location-paint-thickness independence is supported. However, in colder temperatures, drying time is retarded. The paint has time to shift. The logical motion of the paint is to slowly shift to areas where crevices exist. In these instances, the thickness of the paint layers at a single location is not independent. More specifically, a negative specific-location-paint-thickness dependence exists. Areas that are initially low in paint thickness undergo large increases with the next layer addition, while areas that are initially high in paint thickness undergo small increases with the next layer addition.

The DFT gauge probe leaving a dent in the paint following the taking of a measurement is an indication of wet paint. The probe denting the paint results in an inaccurate reading of actual paint thickness [Ref. 9]. To remedy this complication, a piece of plastic of known width, called a shim, is placed between the paint and the probe during measuring. The width of the shim is then subtracted from all measurements obtained to get actual paint thickness readings.

As more data are obtained on the addition of AF paint to existing hull paint systems, a more in-depth analysis of the effects of temperature on the variability of the layers is a logical "next step" for research. The DeFelsko Corporation, a company which manufactures coating thickness gauges, is working on a multi-layer gauge that will measure only the thickness of the AF paint layers that are on the hull. The gauge is expected in the Spring of 1999 [Ref. 9]. Once available for use, this advancement will be a major step in accomplishing this task.

The development of a weighted average to determine the single value estimate of the mean of one coat of AF paint is currently not possible. Thus, the estimate for this analysis is computed to be the "straight" average of the values obtained from the data sets. One coat of AF paint is estimated to have a mean thickness of 6.629 mils, which is approximately 2.6 mils thicker that the NSTM required thickness of four mils [Ref. 14].

The use of a single summary statistic, such as the mean AF paint thickness, can be potentially misleading as an indicator for the entire AF paint distribution on the ship's hull. Adding an estimate for the variance of the thickness of a coat of AF paint provides a better indication of the distribution. However, estimating the variance of the AF paint distribution would require assuming that the variance value remains constant and that the variance of a single coat of paint is independent of the variance of the existing coats of paint. Figures 10 through 13 and research from WWB(1997) show that the variability of the paint coating systems does not remain constant. Also, the limited data listed in Table 3 provides an initial indication that the variability of a single coat is not independent of previously applied coats. So, estimating the variance in the same manner as the mean would not provide valuable information in determining how much paint to add at an interim drydock.

V. MODELLING FUTURE MEAN COATING THICKNESS

Having verified the WWB(1997) model and derived a mean AF coating thickness value, it is now possible to develop a model to estimate the mean thickness of a hull's paint system at a second drydocking given ship evolution information for the two operational cycles.

Let $\hat{q}_d(p)$, for $0 \leq p \leq 1$, be the pth quantiles of the total thickness distribution at the intermediate drydocking estimated using a wear model. Then $\hat{\mu}_d$, the estimate of the mean thickness of the hull paint system at the intermediate drydocking, can be computed using the equation,

$$\hat{\mu}_d = \sum_{i=1}^{100} \hat{q}_d(i / 100) / 100,$$

[Ref. 10].

Now, let $\hat{\mu}_c$ be the estimate of the mean thickness of one coat of AF paint. Having computed $\hat{\mu}_d$, make use of the fact that each added coat of paint adds the same increment of paint, $\hat{\mu}_c$, to the existing system. So, the estimated mean thickness after the application of k coats of AF paint at the intermediate drydocking, denoted $\hat{\mu}_k$, can be computed with the following equation,

$$\hat{\mu}_k = \hat{\mu}_d + k\hat{\mu}_c.$$

To see how this adjusted final paint system changes during the second operational cycle, return to the methodology of the wear model. Namely, for

$0 \le p \le 1$, define $\hat{q}_k(p)$ as the estimate of the pth quantile of the distribution after adding k AF coats at the intermediate drydocking and $\hat{q}_{2d}(p)$ as the estimate of the pth quantile of the distribution at the follow-on drydocking after a second operational cycle. Then,

$$\hat{q}_k(p) = \hat{q}_d(p) + \hat{\mu}_k ,$$

and,

$$\hat{q}_{2d}(p) = \hat{q}_k(p) - \hat{y}_{2d}(p) ,$$

where $\hat{y}_{2d}(p)$ represents the change in paint distribution from the intermediate drydock to the follow-on drydocking, computed using

$$\hat{y}_{2d}(p) = \hat{a} + \hat{b}p ,$$

with the coefficients $\hat{a}$ and $\hat{b}$ coming from the wear model and being functions of the second operational duration, number of hull cleanings and number of hydro-washes. Note that the quantities $\hat{q}_k(p)$ and $\hat{q}_{2d}(p)$ cannot be directly estimated with the data collected. However, using the equations listed above, the mean thickness of the hull paint system can then be estimated as follows:

$$\begin{aligned}
\hat{\mu}_{2d} &= \sum_{i=1}^{100} \hat{q}_{2d}(i/100)/100, \\
&= \sum_{i=1}^{100} [\hat{q}_k(i/100) - \hat{y}_{2d}(i/100)]/100, \\
&= \sum_{i=1}^{100} \hat{q}_k(i/100)/100 - \sum_{i=1}^{100} \hat{y}_{2d}(i/100)/100, \\
&= \hat{\mu}_k - \sum_{i=1}^{100} (\hat{a} + \hat{b}(i/100))/100, \\
&= \hat{\mu}_k - \hat{a} - \hat{b}/100^2 \sum_{i=1}^{100} i.
\end{aligned}$$

Knowing that $\sum_{i=1}^{n} i = n(n+1)/2$, the final equation follows to be,

$$\hat{\mu}_{2d} = \hat{\mu}_k - \hat{a} - \hat{b}(101/200).$$

[Ref. 8].

Modifying this final equation with specific use of the WWB(1997) wear model yields,

$$\hat{y}_{2d}(i/100) = -1.8175 + .0465(i/100) + .4616D + 5.3411C + 4.640W + .0021(i/100)D$$
$$-.0425(i/100)C - .0527(i/100)W,$$

with D, C, and W representing the second operational duration, number of hull cleanings and number of hydro-washes respectively. It follows that,

$$\hat{a} = -1.8175 + .4616D + 5.3411C + 4.640W,$$

and,

$$\hat{b} = .0465 + .0021D - .0425C - .0527W.$$

Thus, the mean thickness of a ship's hull paint system can be estimated by using the SHOMACS software and knowing the number of hull cleanings, hydro-washes and the duration of the ship's second operational cycle with the equation,

$$\hat{\mu}_{2d} = \hat{\mu}_k + 1.8175 - .4616D - 5.3411C - 4.640W - (.0465 + .0021D - .0425C - .0527W)(101/200).$$

A. AN ILLUSTRATION

In August 1996, technicians collected baseline measurements on one of the Navy's newest aircraft carriers, USS Harry E. Truman (CVN 75). This data set has not been used any of the analysis done thus far. As an illustration of the use of the above - derived model for the mean thickness following two operational cycles, an analysis of CVN 75 will be done for a fabricated scenario.

Suppose that during the planning meeting for CVN 75, future shipyard openings are available in the years 2000 and 2006. No hull cleanings are scheduled prior to the 2000 availability, and a hydro-wash is expected prior to measurements if the ship docks. Planners understand that somewhere between 2000 and 2006, the hull will probably require cleaning. They want to know if it is necessary for the ship to be docked at the 2000 opportunity. If the answer to this question is yes, they also want to know what maintenance will be needed at this intermediate drydocking to ensure hull integrity is maintained until the 2006 drydocking? If the answer to this question is no, they want to know if the hull paint system will last until the 2006 opportunity with no service?

Noting that the total operational cycle from 1996 to 2006 is 10 years, it is not reasonable to use the SHOMACS model directly to answer these questions. However, using SHOMACS on the initial data, $\hat{\mu}_d$ is calculated to be 29.288 mils. Current NSTM guidelines require a total average coating measurement of 24-25 mils [Ref 14]. So, the current paint system will survive until the first docking availability.

The developed model is run using the above calculated $\hat{\mu}_d$ with D = 6, C = 1 and W = 0. The value of $\hat{\mu}_k$ is calculated for k = 0, 1, 2, and 3 coats of AF paint. The resulting values for $\hat{\mu}_{2d}$ are 22.987 mils, 29.616 mils, 36.245 mils and 42.874 mils respectively. Thus, planners' questions can be answered as follows: CVN 75 will not last until the 2006 drydock without the addition of AF paint in 2000. Thus, use the 2000 drydock, add at least one coat of AF paint, and the hull paint system will remain in tact until the availability in 2006.

VI. DISCUSSION AND CONCLUSION

In this time of downsizing and cutbacks, the Navy is in search of ways to reduce the overall cost of the fleet. One contributor to total cost is attributed to the physical maintenance and upkeep of ships, specifically hull paint systems. The Navy wants to be able to extend the lifetime of a ship to beyond 12 years in its attempt to decrease costs associated with placing a ship in drydock. However, dangers exist with extended use of current paint systems. Hull surface fouling is an area of major concern, as it reduces a ship's performance and can lead to more severe consequences, such as watertight integrity breaches.

As a first step in arriving at a way to extend survivability while maintaining performance and operability, the WWB(1997) research provides a means for determining how operational duration and hull maintenance procedures affect the wear of a ship's underwater hull coating system. The model does have limitations, though, as stated in Chapter I of this thesis, and thus, cannot be used alone to answer the survivability question as many as 12 years in the future.

This thesis takes a second step toward answering the survivability question by providing a simple model which determines how many coats of AF paint to add to a ship's existing paint system at a future interim drydock in order to ensure the hull remains protected for a second operational cycle. This determination can potentially double the overall lifetime of the ship. It also takes a look at modifying the existing WWB(1997) model to allow for the use of data being collected with an ROV. Although results using data currently available do not facilitate a working modification of the model, as more data becomes available, future research is in this area is viable.

A. RECOMMENDATIONS FOR FUTURE DATA COLLECTION

For the purposes of this analysis and in the derivation of previous models that predict paint wear, operational duration is defined as time elapsed from the initial set of measurements taken to the second set of measurements taken. However, during the course of this analysis, it is noted that descriptions of each ship's operational tempo during these periods show the aircraft carriers undergoing varying lengths of deployments. As an example, the paint system on CVN 74 was initially measured in 1993. A second set of measurements was taken at a follow-on drydock in 1996, but the ship had not deployed in the three years that had elapsed. This raises the question: does the rate of paint wear vary with actual ship operation? A better fitting model may result if operational duration were further divided into deployed and non-deployed durations. Data on the deployment schedules of each ship is not currently being recorded with the collection of DFT data sets at NSWCCD, and thus is not available for use with this thesis.

Determinations for hull maintenance procedures are currently not made at one central location. Some procedures are performed at the request of ship Commanding Officers, while others result from inspections. There is currently no standard record for recording evolutions of a hull cleaning or hydro-washing procedures. Technicians learn of any hydro-wash procedures performed by asking shipyard staff or by witnessing the evolutions personally. Copies of hull cleaning procedure reports are sometimes furnished to NSWCCD. Once the information is obtained, technicians either record their findings in the required trip report for the ship visit, document the procedures with the actual data collected, or both. Although changing the way the procedures are scheduled may not be easily adjusted, centralizing the location of the information once it is obtained at NSWCCD can prove advantageous.

Appendix B contains a sample of a Microsoft Excel Spreadsheet that can be used to remedy the above listed shortcomings. The template is created using a portion of the existing July 1998 data from CV 64. It combines pertinent information currently available from trip reports, technicians and DFT gauges into one concise report, which can be kept in one location, optimally with the Materials Engineer of NSWCCD. Standardization of the data and centralization of its location hold the great advantage of making future collection evolutions and research evolutions easier.

B. ADVANTAGE OF MODEL USE IN THE FLEET

Based on advancements made prior to this research, the Standard Items 009-31 directive is in transition, currently allowing for the four hull maintenance options of no work, complete removal, partial removal or touchup work instead of the one worst-case option [Ref. 9]. The extension of past advancements with this research will result in less "open ended" estimation and more quantitatively-based estimation of future hull maintenance procedures, thus taking the Navy another step in the direction of its goal to reduce drydock costs. This entire analysis was done using only aircraft carriers, but the information gained should serve as a conservative estimate for all types of ships in the fleet, as aircraft carriers typically have the more intense operational schedules than other surface ships.

APPENDIX A. DATA AVAIALBLE FOR ANALYSIS

Hull Number	Month-Year Data Collected
CV 59	Oct-90
CV 59	Sep-92
CV 63	Jan-98
CV 63	Mar-98
CV 64	Apr-97
CV 64	May-98
CV 64	Jul-98
CV 66	Unknown-85
CV 66	Jul-86
CV 66	Jul-92
CV 67	Nov-94
CV 67	Apr-97
CVN 65	Jun-91
CVN 68	Feb-90
CVN 68	Feb-94
CVN 68	May-98
CVN 69	Jul-85
CVN 69	Jan-93
CVN 69	Jul-95
CVN 69	Oct-95
CVN 69	Jun-96
CVN 71	Feb-92
CVN 71	Jul-97
CVN 71	Jan-98
CVN 72	May-90
CVN 72	Mar-95
CVN 72	Jan-96
CVN 73	Jan-93
CVN 73	Jul-97
CVN 73	Jun-98
CVN 74	Oct-93
CVN 74	Aug-96
CVN 74	Sep-97
CVN 75	Aug-96

APPENDIX B. TEMPLATE FOR USE IN FUTURE DATA COLLECTION

UNDERWATER HULL PAINT SYSTEM DATA SET

Place visited: Puget Sound Naval Shipyard
Ship Visited (name and hull number): USS Constellation (CV 64)
Date (mo/yr) visited: Jul-98
Visited by: T. Radakovich
Description of reason for visit: Drydock: After AF paint app.

Date (mo/yr) of last measurements: May-98
No. hull cleanings since last measurements: 0
No. hydro-washes since last measurements: 0
Time (mos) deployed since last measurements: 0

Total number of data points: 20
Maximum reading: 62.6063
Mimimum reading: 26.0083
Average reading: 46.55164

Raw data	Sorted data	Bin	Freq.	Dist.	Cum. Dist.
62.6063	26.0083	0	0	0	0
47.4396	38.7201	2	0	0	0
49.7269	39.087	4	0	0	0
55.9814	40.534	6	0	0	0
54.1204	40.5525	8	0	0	0
47.0729	41.5992	10	0	0	0
40.534	42.8532	12	0	0	0
42.8532	44.0075	14	0	0	0
40.5525	44.106	16	0	0	0
41.5992	47.0729	18	0	0	0
44.106	47.4396	20	0	0	0
44.0075	49.7269	22	0	0	0
51.0507	50.2676	24	0	0	0
51.0241	51.0241	26	0	0	0
52.7725	51.0507	28	1	5	5
50.2676	51.5026	30	0	0	5
26.0083	52.7725	32	0	0	5
51.5026	54.1204	34	0	0	5
39.087	55.9814	36	0	0	5
38.7201	62.6063	38	0	0	5
		40	2	10	15
		42	3	15	30
		44	1	5	35
		46	2	10	45
		48	2	10	55
		50	1	5	60
		52	4	20	80
		54	1	5	85
		56	2	10	95
		58	0	0	95
			1	5	100

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